Polarized atomic hydrogen targets
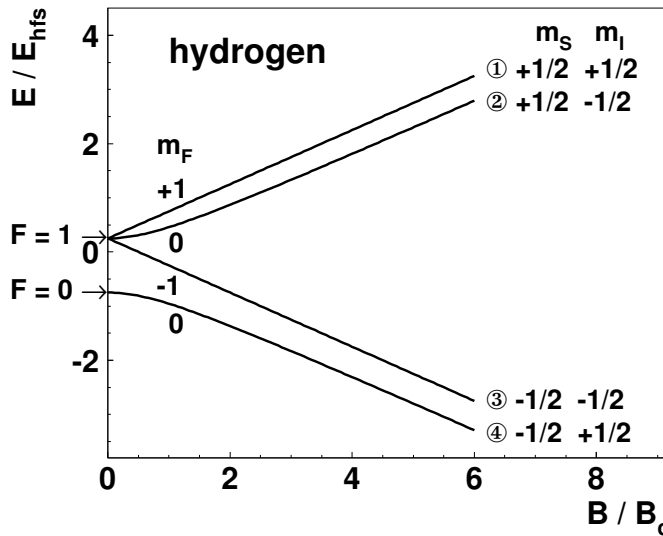
1. Hyperfine states and polarization

2. Atomic beam sources

   (a) Dissociator
   (b) Beam formation
   (c) Sextupole system
   (d) High frequency transitions

3. Jets or storage cells

4. Depolarization effects

5. Diagnistics: Breit Rabi polarimeter

6. Summary

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Hyperfine states and polarization

$$|1\rangle = |+\tfrac{1}{2}, +\tfrac{1}{2}\rangle$$

$$|2\rangle = \cos\theta\,|+\tfrac{1}{2}, -\tfrac{1}{2}\rangle + \sin\theta\,|-\tfrac{1}{2}, +\tfrac{1}{2}\rangle$$

$$|3\rangle = |-\tfrac{1}{2}, -\tfrac{1}{2}\rangle$$

$$|4\rangle = \cos\theta\,|-\tfrac{1}{2}, +\tfrac{1}{2}\rangle - \sin\theta\,|+\tfrac{1}{2}, -\tfrac{1}{2}\rangle$$

with $\theta = \tfrac{1}{2}\arctan\tfrac{B_c}{B}$

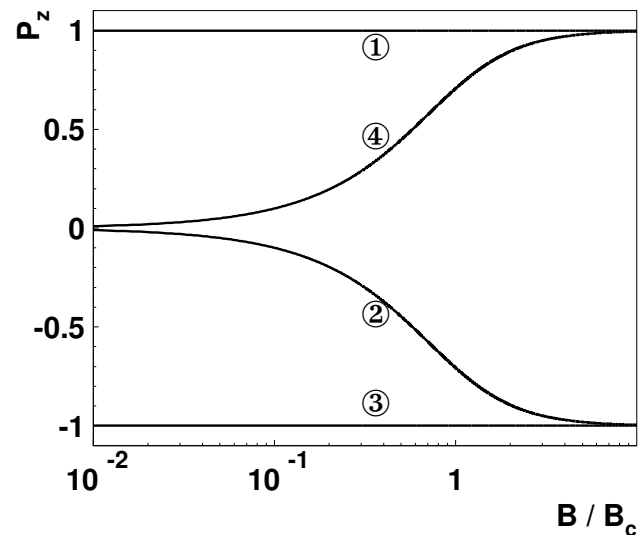$$(B_c = 50.7mT)$$

$$P_e = n_1 - n_3 + (n_2 - n_4)\cos 2\theta$$

$$\overset{B\to\infty}{\Longrightarrow} n_1 + n_2 - n_3 - n_4$$

$$\overset{B\to 0}{\Longrightarrow} n_1 - n_3$$

$$P_z = n_1 - n_3 + (n_4 - n_2)\cos 2\theta$$

$$\overset{B\to\infty}{\Longrightarrow} n_1 + n_4 - n_2 - n_3$$

$$\overset{B\to 0}{\Longrightarrow} n_1 - n_3$$

$\Rightarrow$ Strength of target holding field B defines the maximum polarization

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The JET polarized hydrogen beam target at RHIC

Dissociator

Sextupoles

SFT
WFT

Holding
field magnet

Sextupoles

SFT

WFT

BRP detector
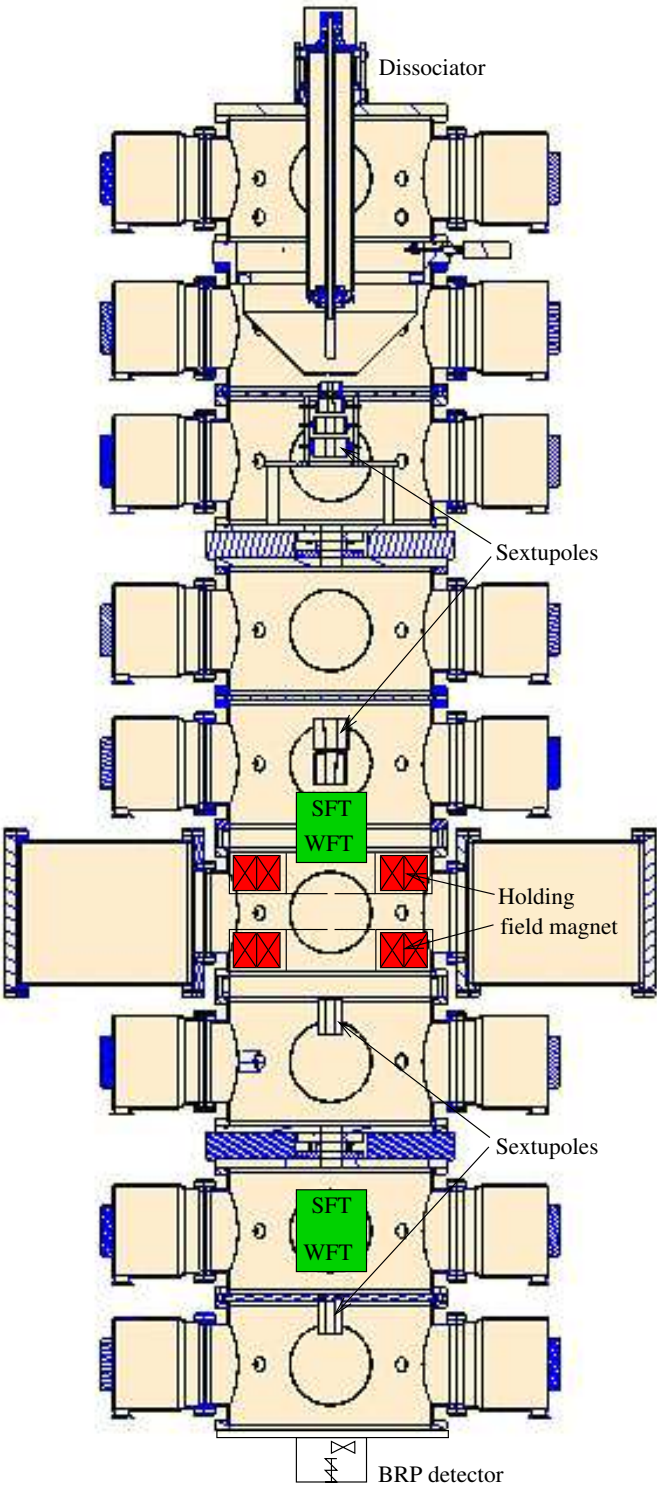
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Dissociator at the JET

(A.Zelenski)
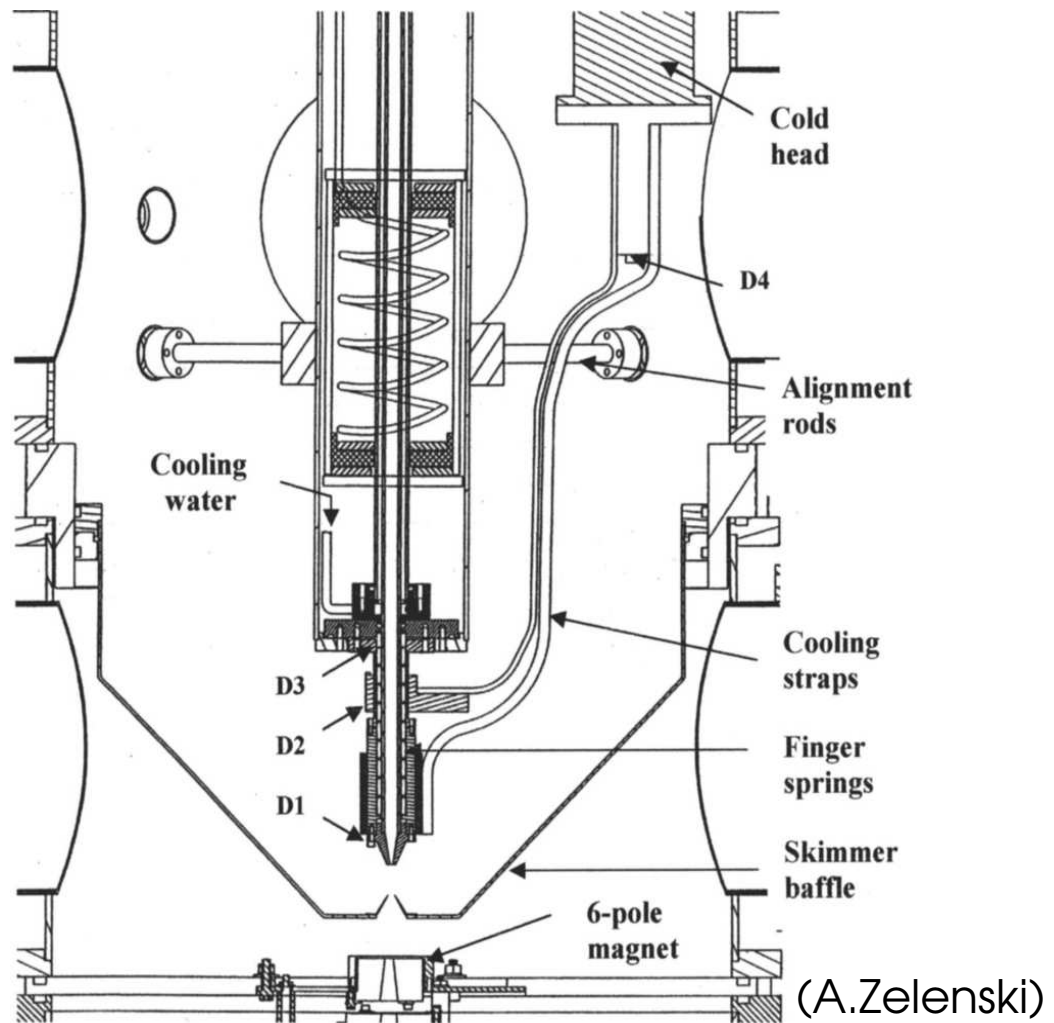
- Plasma source consists of LC-circuit at variable frequency (≈ 21 MHz), typical applied RF-power: $250 \ldots 300$ W
- Slightly different frequencies used at other sources (Bates, HERMES 13.6 MHz), but matching elements required
- Water cooled discharge tube
- Degree of dissociation $\alpha = \frac{N_1}{N_1 + 2N_2} \approx 80\%$ at 1mbarl/s

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Dissociation:

Exitation of H_2-molecules to repulsive states via electron impact

$$H_2 + e^- \quad \rightarrow \quad H_2^{**} + e^- \qquad \rightarrow 2H + e^- \qquad (1)$$

$$\rightarrow H^+ + H + 2e^- \quad (2)$$

Recombination:

$$H + H + M \rightarrow H_2 + M \qquad (3)$$
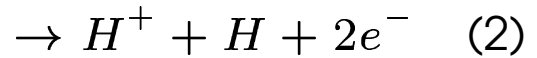
- 3–body collision (conservation of energy and momentum)

- M determined by mean free path λ:

  - $\lambda \ll d \rightarrow M = H, H_2$ (d - diameter of the discharge tube)

    $\Longrightarrow$ Volume recombination

  - $\lambda \approx d \rightarrow M = Si, O$

    $\Longrightarrow$ Wall recombination

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Formation of the atomic beam

- Expansion of highly dissociated hydrogen gas through a cold (60-100K) nozzle $\Rightarrow$ acceleration of the atoms ($v_{H_1} \approx 1500 \ldots 2000$ m/s)
- High brilliance beam formed by skimmer and collimator
- Divergence of the beam has to match the relatively small acceptance of the sextupole magnet system
- Parameters of the beam are defined by the pressure in front of the nozzle (p_0) and the nozzle temperature (T_0)

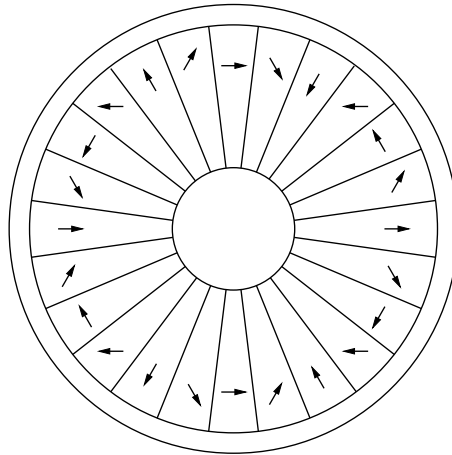 e.g. the maximal velocity of the beam ($p_0 \to \infty$):

$$v_\infty = \sqrt{\frac{2k_B}{m} \left(\frac{\gamma}{\gamma - 1} \right) T_0} \tag{4}$$

density distribution:
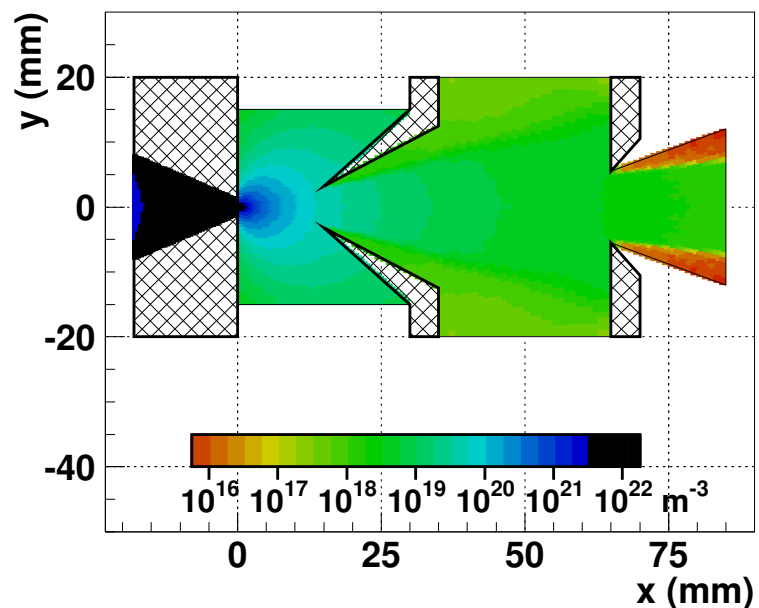
Separation according to electron spin state

- Force on the atom:

$$\vec{F} = -\nabla E = -\frac{\partial E}{\partial B} \cdot \frac{\partial B}{\partial r} \vec{e_r} = -\mu_{eff} \cdot B_0 \frac{r}{2r_0^2} \vec{e_r} \quad (5)$$

  (pole tip field $B_0 \approx 1.5$ T (JET) and pole tip radius r_0)
- At high fields:

$$m_j = +\frac{1}{2} : \quad \mu_{eff} = +\mu_B \quad \Longrightarrow \vec{F}/\vec{e_r} < 0 \quad (6)$$

$$m_j = -\frac{1}{2} : \quad \mu_{eff} = -\mu_B \quad \Longrightarrow \vec{F}/\vec{e_r} > 0 \quad (7)$$

- $\Longrightarrow$ Atoms with $m_j = +\frac{1}{2}$ focussed towards the center
  $\Longrightarrow$ Atoms with $m_j = -\frac{1}{2}$ deflected from the center

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- Trajectory of a $m_S = +1/2$ atom from equations (6) to (8):
$$r(z) = r_e \sin(\Lambda z) + r_e \cos(\Lambda z) \qquad (8)$$
where z - axial position, r_e - radial position and focal length:
$$\frac{1}{\Lambda} = r_0 v_z \sqrt{\frac{m_a}{2\mu_B B_0}} \qquad (9)$$

- For atoms with $m_S = -1/2$ replace trigonometric functions by corresponding hyperbolic functions

- Usage of genetic algorithms to create of sextupole magnet systems with optimized transmission for the beam parameters given

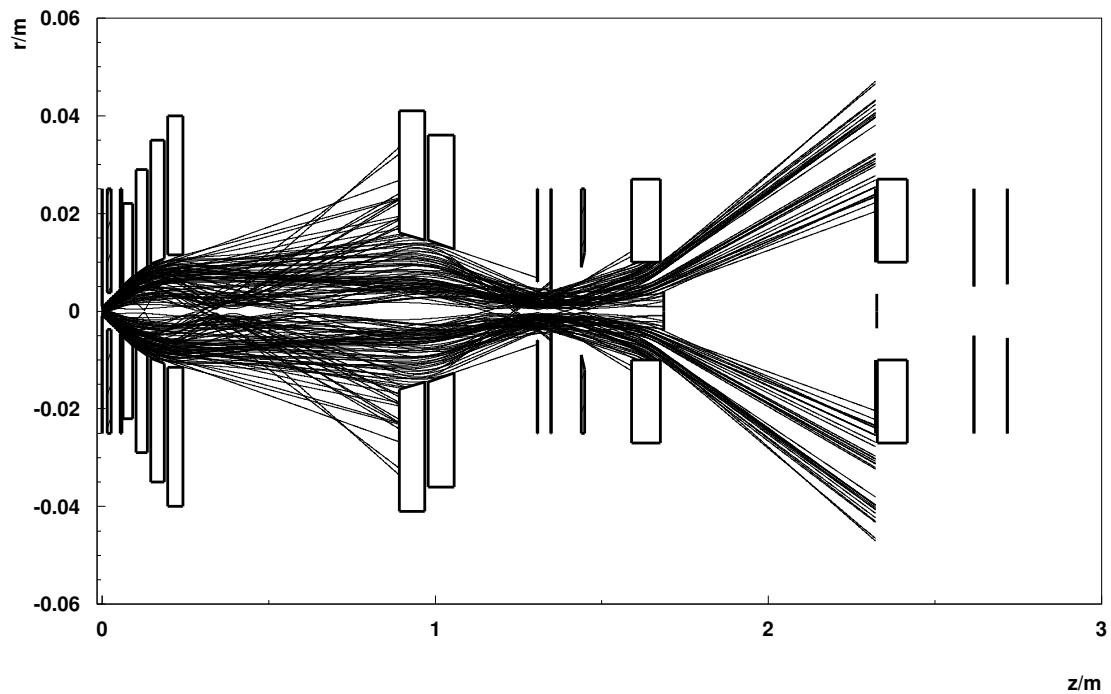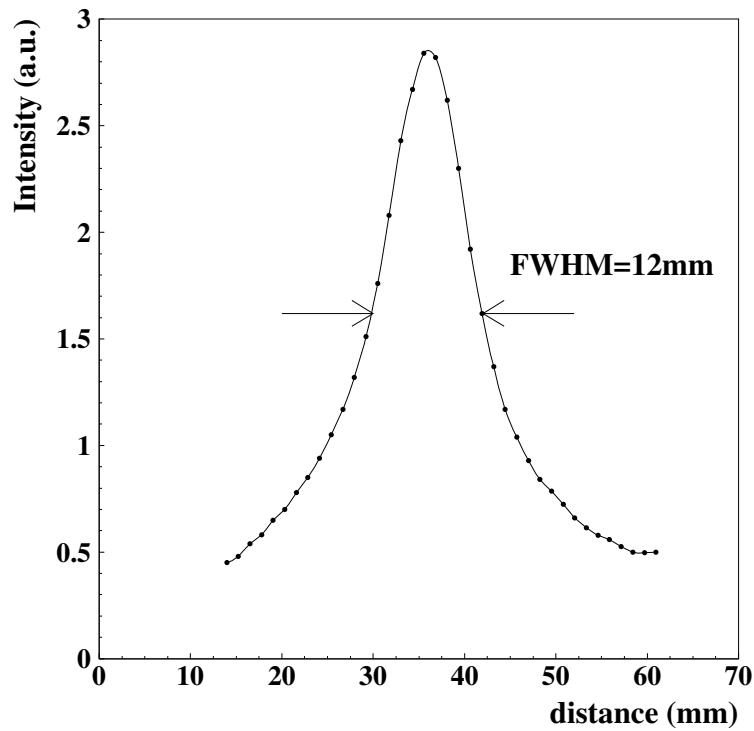## Tracking of state $|1\rangle$ through the system (T. Wise)
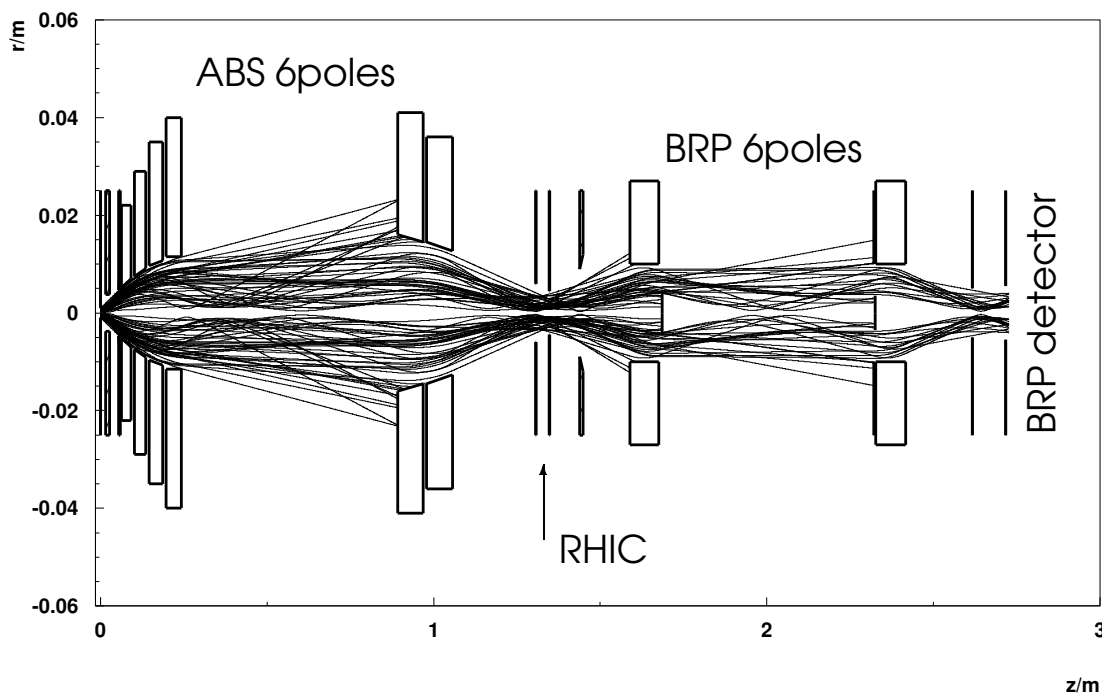
Tracking of state $|1\rangle$ exchanged to $|3\rangle$ in BRP WFT
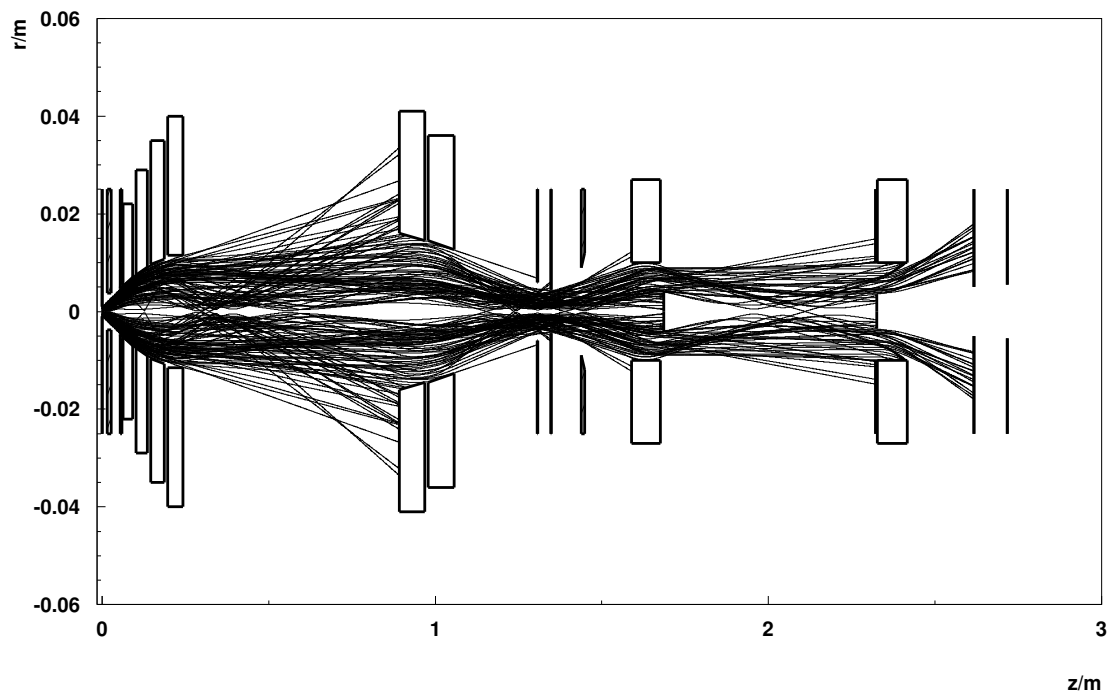
Tracking of state $|1\rangle$ exchanged to $|3\rangle$ in ABS WFT

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Beam profile in between the sextupole magnets

Beam profile at RHIC intersection point

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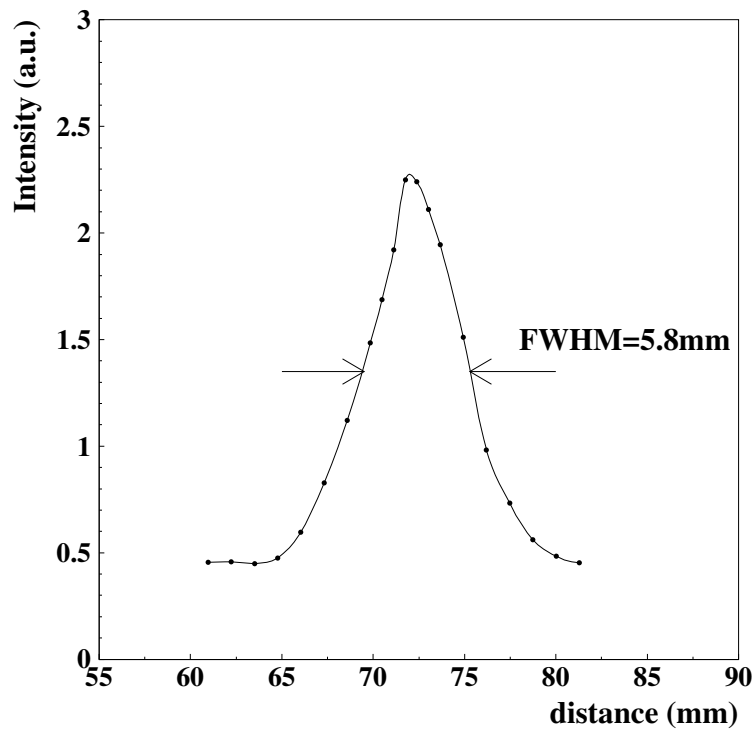
Intensity optimization

Intensity vs. nozzle temperature
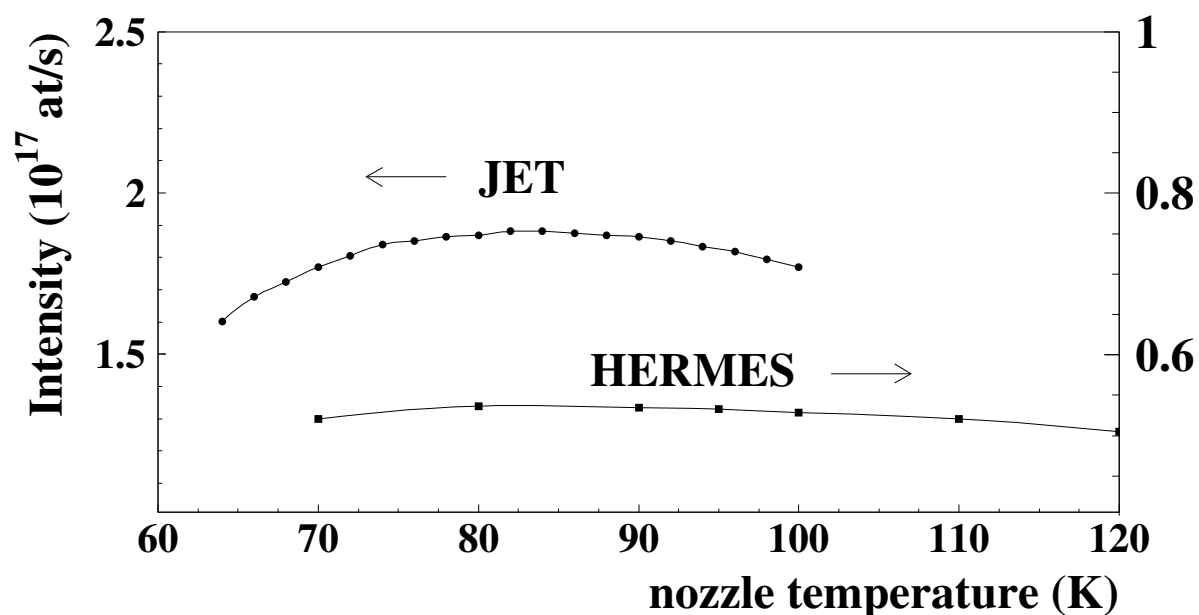
Intensity vs. hydrogen flux through the dissociator

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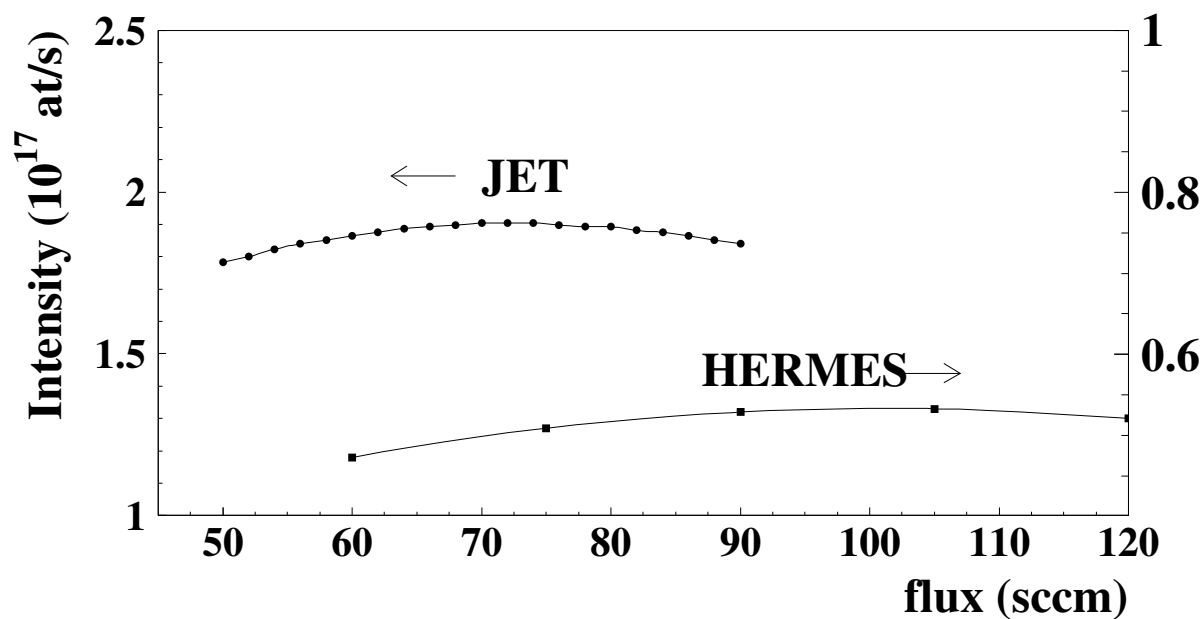
Intensity optimization

Intensity vs. oxygen flux through the dissociator
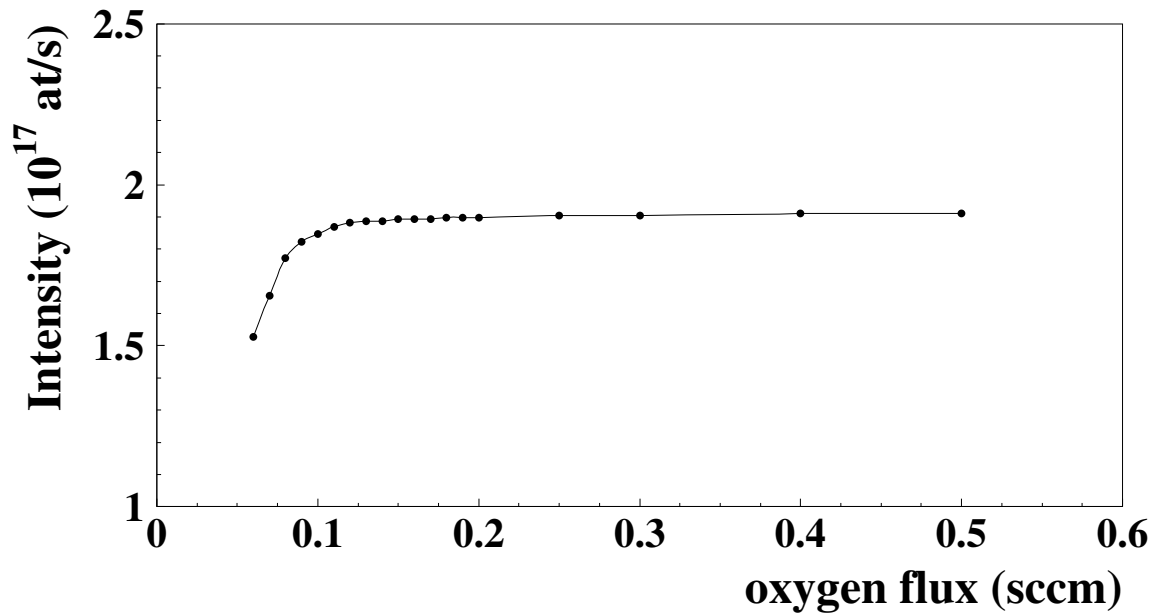
- O_2 needed for high degree of dissociation in the dissociator
- Reduced recombination on the glass tube wall

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Background

Unpolarized nucleons in hydrogen molecules

- Insertion of a QMA in chamber #6 (later RHIC interaction point)
- Measured density ratios H/H_2
- Measurements includes H_2 from beam and background
- Calibration of the total H_2 density
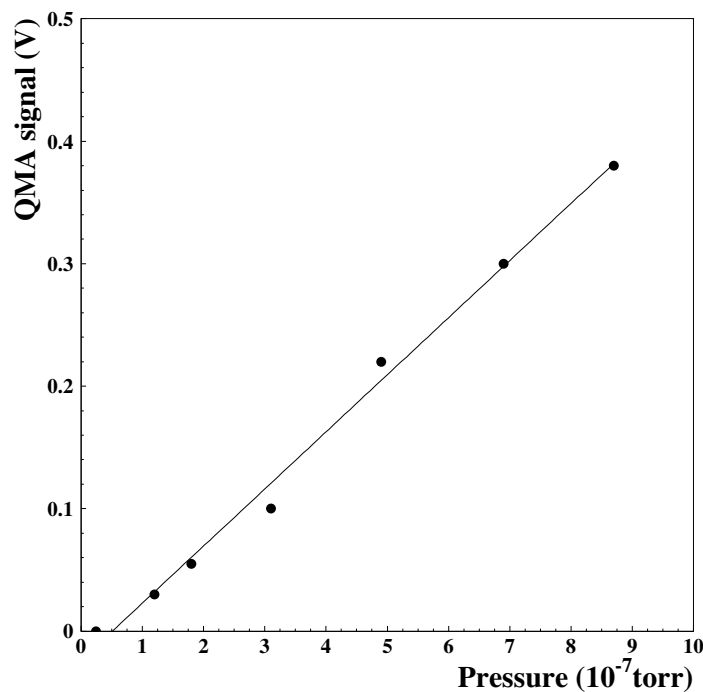
$\Rightarrow$ Density fraction of unpolarized nucleons in $H_2 \leq 3\%$ ($\alpha = 97\%$)

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Adiabatic high frequency transitions

Change of occupation numbers inbetween hyperfine states

- HFT's consist of a constant field, a gradient field and a high frequency field
- High frequency = transition frequency between 2 hyperfine substates in the static field
- 3 types of HF-transitions:

Weak field transition (WFT) $|\Delta F| = 0,\, m_F \to -m_F$
Medium field transition (MFT) $|\Delta F| = 0,\, |\Delta m_F| = 1$
Strong field transition (SFT) $|\Delta F| = 1,\, |\Delta m_F| = 0$
$$|\Delta m_F| = 1$$

E

$m_F = +1$

①

F=1 $m_F = 0$

②

③ $m_F = -1$ B

④

F=0 $m_F = 0$

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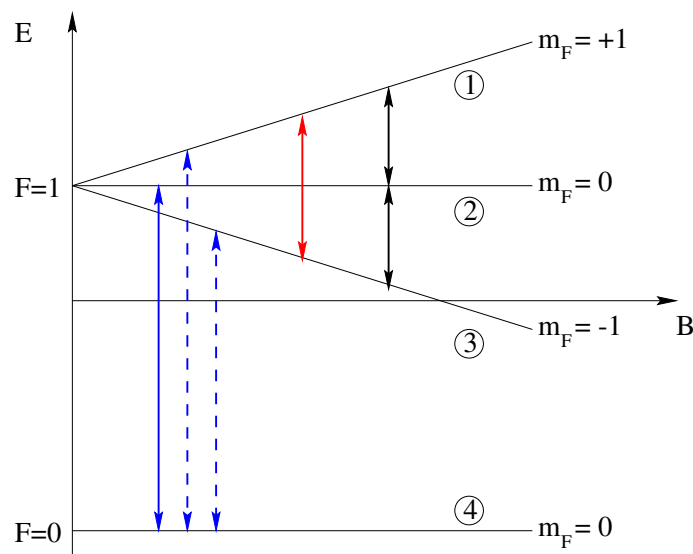
Quantum mechanical description of HFT's

- Start with 2 states with exact analytical solutions in space fixed coordinates
- Transformation to rotating coordinates around the z–axis with rotation frequency $\omega_L = \gamma B$
  - Hamiltonian still diagonal
    $\rightarrow$ $|1\rangle$ and $|2\rangle$ still Eigenstates of Hamiltonian
  - Energy eigenvalues shifted by constant values
- HF magnetic field as perturbation to the Hamiltonian:

$$H = H_0 + V_{HF} \tag{10}$$

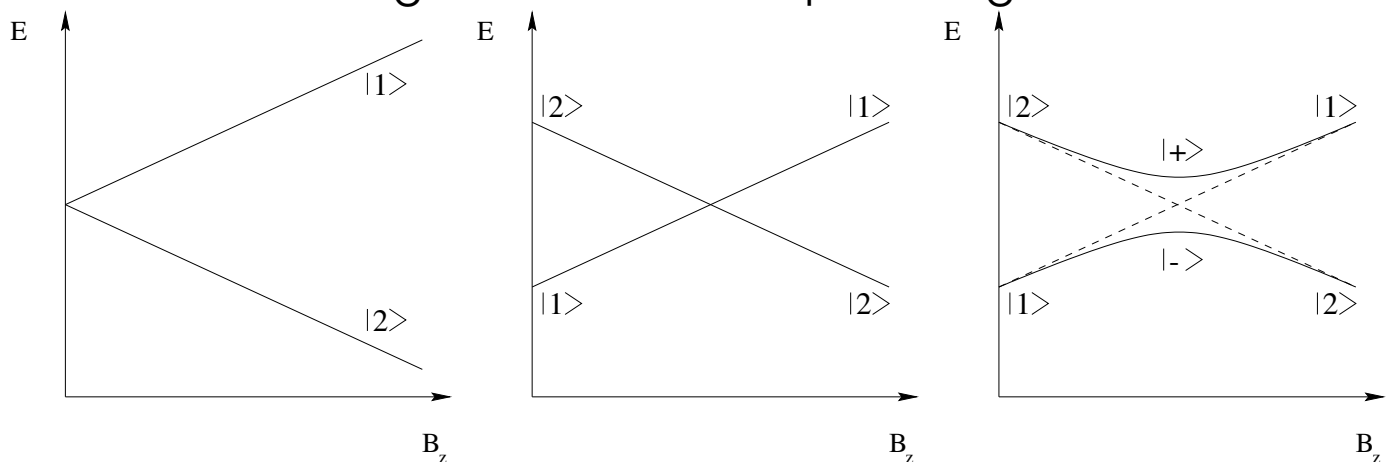- New Eigenstates:

$$|+\rangle = \cos\phi\,|1\rangle + \sin\phi\,|2\rangle \tag{11}$$

$$|-\rangle = \sin\phi\,|1\rangle - \cos\phi\,|2\rangle \tag{12}$$

ϕ – mixture of static field $B_{0,z}(t)$ and HF–field B_{HF}

- Transition from $|1\rangle$ to $|2\rangle$ if atom with Eigenvector $|-\rangle$ moves through static field with positive gradient

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- Probability for passing the energy gap:

$$p = e^{-2\pi\kappa} \quad \text{with} \quad \kappa = \left| \frac{\mu_s B_{HF}^2}{2\dot{B}_{0,z}\hbar} \right| \quad (13)$$

- Adiabatic transition if atom stays in Eigenstate $|+\rangle$ (or $|-\rangle$) during $\dot{B}_{0,z}$ and $p \ll 1$

$$\Longrightarrow \mu_s B_{HF}^2 \gg 2\dot{B}_{0,z}\hbar \quad (14)$$

- In praxis (B_0 - static gradient field, B_1 - HF-field):
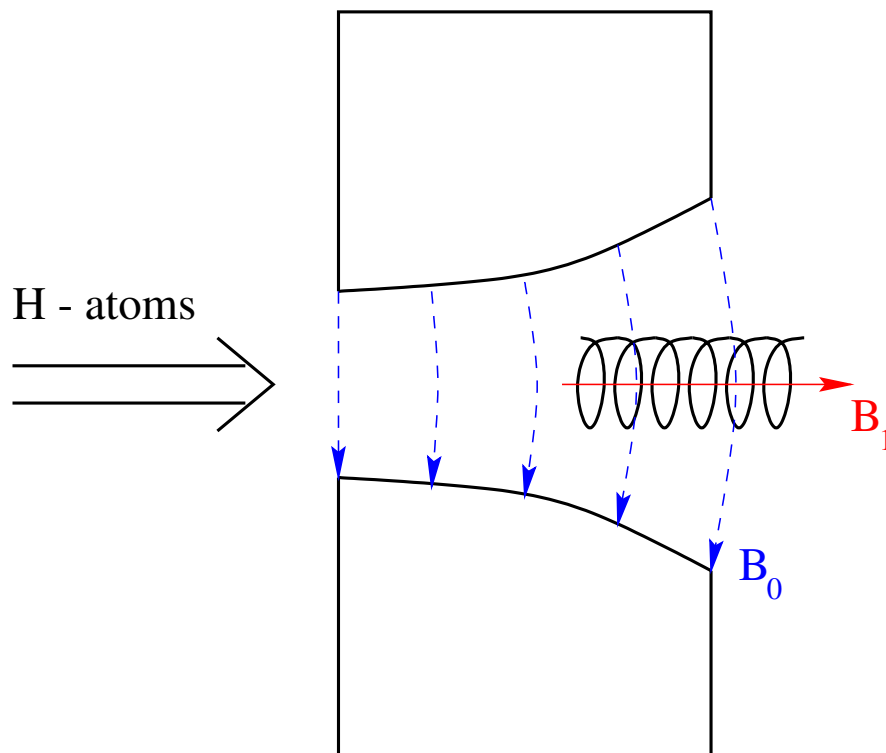
- <u>But</u> stray fields can cause additional transitions !!!

Setup of the adiabatic HFT's
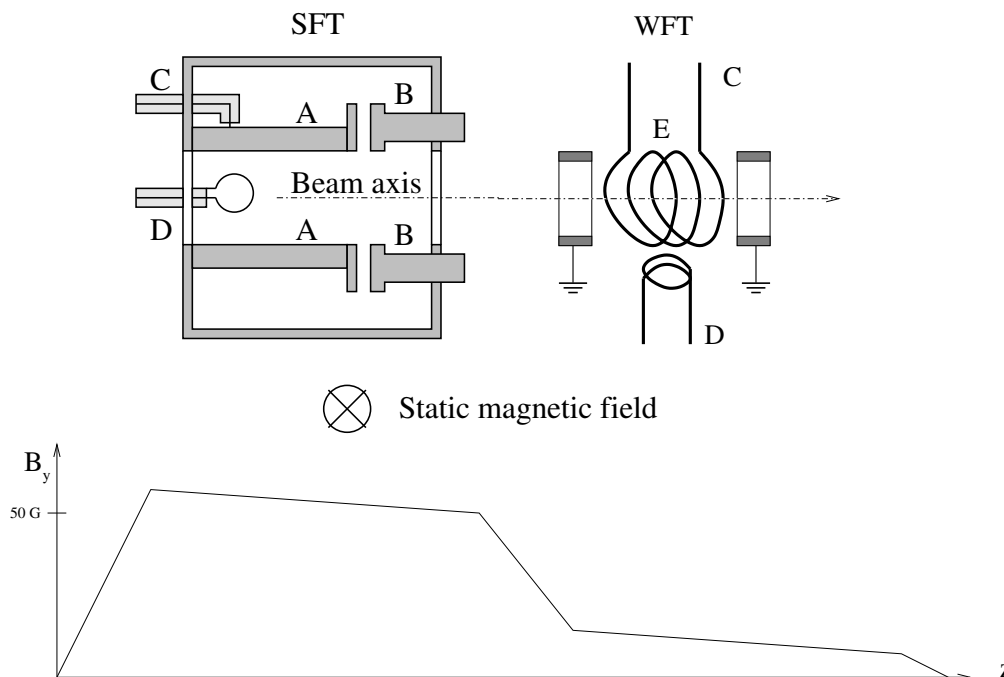
- Static magnetic field = main field + gradient field
- SFT:
  - Cavity with resonator rods (A) + adjustable capacitor plates (B) for tune to suitable frequency (1.43 GHz)
  - RF power input (C) and pickup loop (D)
  - RF coupled to one of the rods
    $\Rightarrow$ 2nd rod is excited by this field
    $\Rightarrow$ RF fields interfere constructively on beam axis
  - Feedback loop to compensate for heating effects
- WFT:
  - RF coil (E) to couple 14 MHz
  - Impedance matching with a matching box

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Combination of HFT's and sextupoles

initial states	1+2+3+4	1+2+3+4	1+2+3+4
after 6-poles	1+2	1+2	1+2
after WFT (1-3)	off 1+2	off 1+2	on 2+3
after SFT (2-4)	off 1+2	on 1+4	off 2+3
$P_e(B \to \infty)$	+1	0	0
$P_z(B \to \infty)$	0	+1	-1

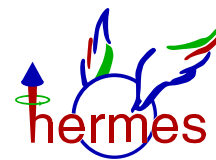Alexander Naß, Brookhaven National Laboratory

Jets or storage cell

Jet target:

- An accelerated beam (e, p) is colliding with the atoms of the free polarized atomic beam
- Since FOM $\sim$ Density $\cdot$ (Polarisation)^2
  $\Rightarrow$ High density required $\Rightarrow$ high intensity atomic beam at a preferably low mean velocity
- Low H_2 content in the beam (H_2 are unpolarized)
- High nuclear polarization of the atoms

Storage cell (required for high density targets):

- An accelerated beam (e, p) is colliding with polarized atoms in a storage cell provided by an ABS
- Since FOM $\sim$ Intensity $\cdot$ (Polarisation)^2
  $\Rightarrow$ High beam intensity at a higher mean velocity
- Low H_2 content in the beam (H_2 are unpolarized)
- High nuclear polarization of the atoms
- Polarization preserving coating on the storage cell walls
- Low storage cell temperatures to increase the target density

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The HERMES polarized hydrogen gas target

target gas analyser

quadrupole–mass spectrometer

quadrupole–mass spectrometer

chopper

chopper

dissociator

H_2

skimmer

collimator

SFT
MFT

WFT
SFT

e

MFT sextupole magnets

SFT

Breit–Rabi polarimeter

sextupole magnets

atomic beam source

storage cell

hermes

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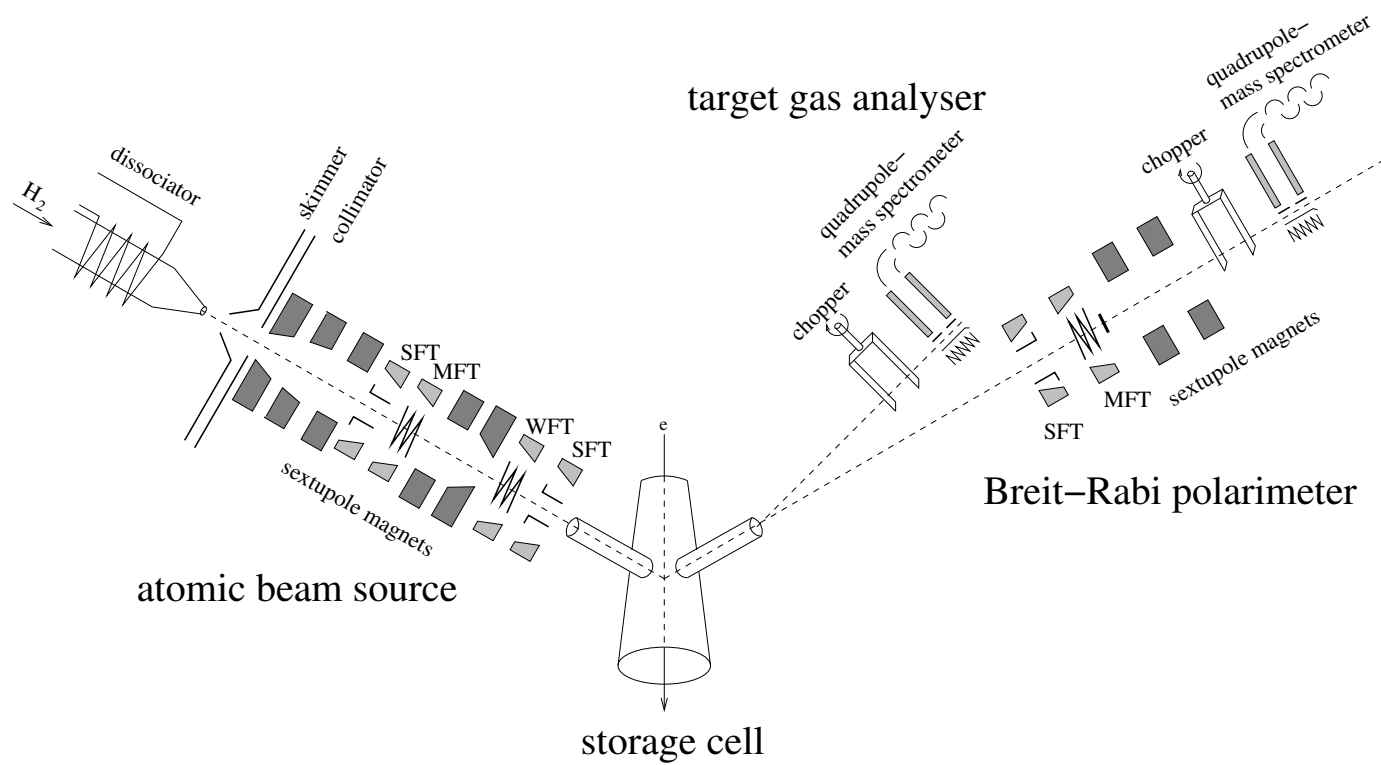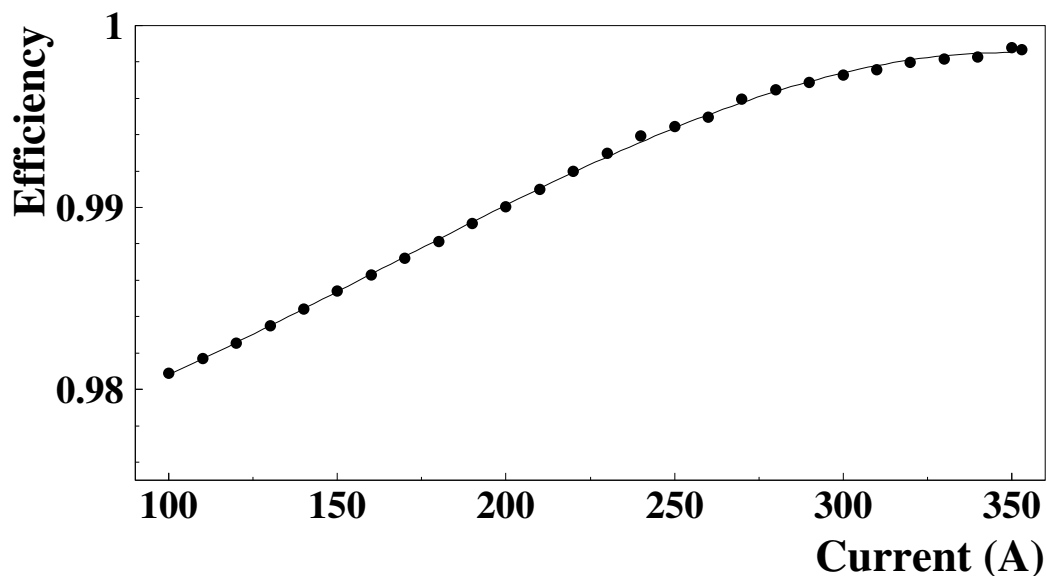
Depolarization effects

Non adiabatic transitions

- Change of magnetic field strength and direction on the path of the atoms $\Rightarrow$ Time-dependent magnetic field in rest frame of the atoms
- Majorana depolarization if time dependence of these fields is too rapid
- No depolarization if field changes are 'adiabatic', e.g. that a change in field direction seen by the atoms is slow compared to the Larmor time t_L of the atoms in that field
- Since $t_L \sim 1/B$ a strong B is allowed to change rapidly in direction, while a weak B must change only gradually in direction

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Depolarization effects

Beam induced depolarization

- Bunched e or p beam $\Rightarrow$ transient magnetic fields transverse to the beam direction
- Closely spaced depolarizing resonances in the usable range of the surrounding target holding field

$\Rightarrow$ High uniformity of the target holding field over the entire target region and careful choice of working point.

Required at JET: $\Delta B/B = 3 \cdot 10^{-3}$, achieved $2 \cdot 10^{-3}$

Breit Rabi polarimeter (BRP) at JET

- BRP used to measure the atomic beam polarization
- Consists of:
  - permanent sextupole magnets to separate states $|1\rangle$ and $|2\rangle$ from states $|3\rangle$ and $|4\rangle$
  - HFT's (WFT and SFT) to exchange populations of states $|1\rangle \leftrightarrow |3\rangle$ and $|2\rangle \leftrightarrow |4\rangle$
  - detector with chopper to measure the signal without background (ion gauge)
  - beam blockers to prevent molecules and states $|3\rangle$ and $|4\rangle$ leaking through on the beam axis
- State $|1\rangle$ and $|2\rangle$ not deflected by the sextupole magnets but different transmission through sextupole system due to nuclear spin (ratio N_1/N_2)

$\Rightarrow$ At least 6 different settings required to determine the unknown ABS and BRP HFT efficiencies ϵ_{1-3}, ϵ'_{1-3}, ϵ_{2-4}, ϵ'_{2-4} and N_1/N_2

$\Rightarrow$ Polarization:

$$P^+ = \frac{1 + \cos\theta \frac{N_2}{N_1} - 2\cos\theta \epsilon_{2-4} \frac{N_2}{N_1}}{1 + \frac{N_2}{N_1}} \qquad (15)$$

$$P^- = \frac{-1 - \cos\theta \frac{N_2}{N_1} + 2\epsilon_{1-3} \frac{N_2}{N_1}}{1 + \frac{N_2}{N_1}} \qquad (16)$$

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Combination of HFT's and sextupoles

	1+2+3+4		1+2+3+4		1+2+3+4	
initial states	1+2+3+4		1+2+3+4		1+2+3+4	
after 6-poles	1+2		1+2		1+2	
after WFT (1-3)	off 1+2		off 1+2		on 2+3	
after SFT (2-4)	off 1+2		on 1+4		off 2+3	
$P_e(B \to \infty)$	+1		0		0	
$P_z(B \to \infty)$	0		+1		-1	
after BRP-6-pole #1	1+2		1		2	
after BRP-WFT (1-3)	off 1+2	on 2+3	off 1	on 3	off 2	off 2
after BRP-SFT (2-4)	off 1+2	off 2+3	off 1	off 3	off 2	on 4
after BRP-6-pole #2	1+2	2	1	-	2	-
Detector signal	100%	50%	50%	0%	50%	0%
Signal (V)	2.8	1.401	1.401	0.002	1.401	0.002

$\Rightarrow$ HFT efficiencies > 99.9%
$\Rightarrow$ Influence of systematics very low

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Velocity measurements

- Beam density $\propto$ beam intensity / velocity
- Insertion of a QMA in chamber #9 (BRP chamber)
- Both ABS transitions running $\to$ no signal due to deflection of states $|3\rangle$ and $|4\rangle$ in the BRP sextupoles
- Short interuption of ABS SFT running $\to$ package of atoms arriving at QMA after some drift time through BRP
- TOF spectrum measured with oscilloscope using the RF pick-up amplitude of the SFT as trigger
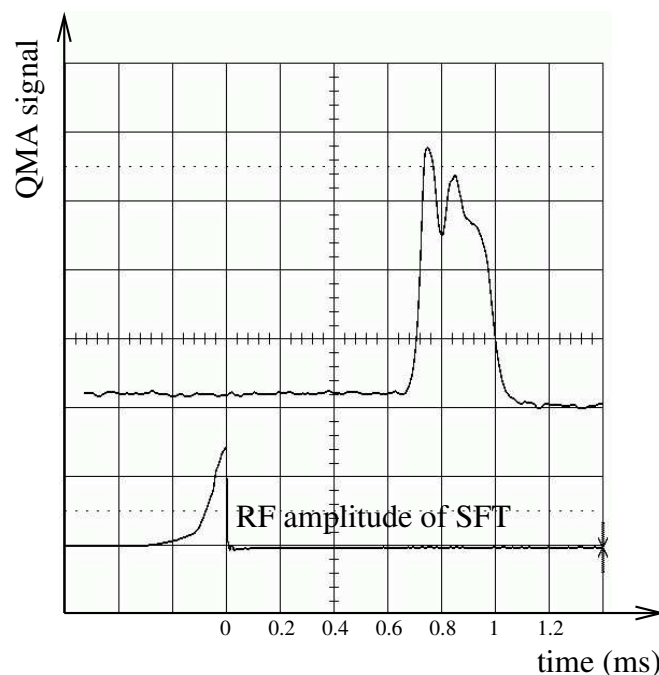
Spectrum affected by transmission through the BRP 6poles
$\Rightarrow$ Correction with transmission simulations or

Insertion of a mechanical chopper in chamber #4 and QMA in chamber #6

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Summary and outlook

- Internal hydrogen gas targets or jets provide highly polarized atomic sample to an accelerated e or p beam ($P_{JET} \approx 95\%$ at $B = 1$ kG)
- Intensity of the JET beam $\approx 2 \cdot 10^{17}$ atoms/s
- Density of the JET beam $\approx 10^{12}$ atoms/s
- Very small dilution by unpolarized nucleons in molecules ($\alpha_{JET} \geq 97\ \%$)
- Fast switching of the polarization (some ms) with highly efficient HFT's ($\epsilon_{HFT} > 99.9\%$)
- On line determination of target polarization

Next steps

- Setup of an electron gun and extraction devices to monitor the molecular content of the beam on line

e
gun

60

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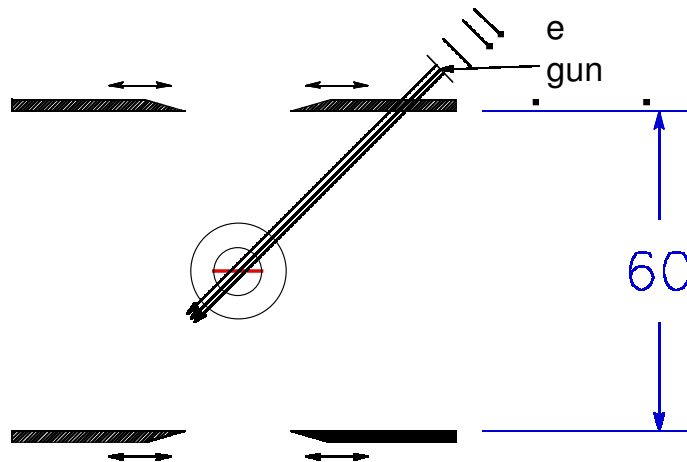
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